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Architectures and Devices for Millimeter Wave Imaging

by David A. Wikner, Joseph N. Mait, and Mark Mirotznik

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14. ABSTRACT

A research effort was conducted to explore the ways in which sub-wavelength gratings can be used to reduce the reflections from the optics of millimeter-wave imaging systems. A moth-eye lens is sometimes used at optical and infrared frequencies for this purpose, but it is too fragile to be applied directly to the plastic lenses used in the millimeter-wave. A modification of this structure, called the inverse moth-eye lens, was designed, fabricated, and tested. Within the report we present results at 35 GHz showing a 15-dB reduction of surface reflections in Rexolite. The technique was also applied to a material with a dielectric constant of 9. Transmission increased an average of about 30 dB between 30 and 40 GHz with the inverse moth-eye, anti-reflection (AR) surface. The implication of these results is that the weight and bulk of millimeter-wave imaging systems could be significantly reduced by using optical systems with high dielectric materials and etched, sub-wavelength AR surfaces.

15. SUBJECT TERMS

Millimeter wave imaging, lens, anti-reflection

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1. Objective

This research effort sought to develop architectures for millimeter-wave (MMW) imaging systems that use novel MMW optical designs and advanced MMW detector arrays. The objective was to design and demonstrate these architectures for compact MMW imaging systems. The work focused on techniques that are newly applied to this frequency band to create optical designs that insure small size and weight without compromising imaging performance.

2. Approach

The program has involved the modeling, fabrication, and testing of improved optical elements for MMW imaging systems. Promising optical designs included those that were capable of reducing the volume and weight of existing MMW optics without sacrificing performance. A goal of the effort has been to develop these optics for an existing U.S. Army Research Laboratory (ARL) MMW imager. This imager uses two lenses to focus energy onto a focal plane array. These lenses are made of the plastic Rexolite™, are several inches thick, and weigh about 9 lb each. The reason that these lenses are so large is because the f-number of the optical system is about 1.5. This is done to minimize the depth (volume) of the imager. Two lenses are needed to correct aberrations caused by having a detector array that is 2/3 the diameter of the objective lens. These geometric constraints cannot be changed, because they are fixed by the 3-mm wavelength and the sensor size limits of Army platforms. Therefore, this Director's Research Initiative (DRI) program has pursued methods of reducing lens thickness by modeling and measuring anti-reflection (AR) surfaces in both Rexolite and higher dielectric constant materials.

The concept of increasing the dielectric constant to reduce lens thickness is straight forward. The problem is that more radio frequency (RF) energy is lost due to surface reflections and absorption. In this effort, we first addressed the issue of surface reflections. AR coatings are often applied to the surface of passive components, such as lenses, to suppress Fresnel reflections and, as a consequence, collect more energy in the desired waveband. The most common method for implementing broadband AR surfaces is to coat the surface with multiple layers of thin films. Various optimization algorithms are used to determine exact values for the number of layers, dielectric constants of the films, and their respective thicknesses such that the coating produces the least amount of reflected energy over the desired spectral band. In general, as the number of layers in the coating increases, the antireflective behavior improves. Unfortunately, implementing this same approach at millimeter wavelengths can be challenging since finding materials with the desired dielectric constants is difficult. An alternative method, originally

developed for designing AR surfaces in visible and infrared applications, uses a multi-level sub-wavelength grating fabricated directly on the surface of a dielectric (*1–3*). This technique was biologically inspired by the sub-wavelength surface pattern on the cornea of the common insects including many moths and many butterflies. Consequently, manmade AR surfaces of this type are often called "moth-eye" surfaces. Similar to the conventional thin film AR coatings, the performance of moth-eye AR surfaces improves as the number of levels increases. Unfortunately, most multi-level designs of conventional moth-eye AR surfaces result in very thin needle-like structures protruding from the surface of a dielectric (figure 1). These structures can be difficult to fabricate and often lack the mechanical rigidity required for some applications. In our work, we pursued an alternative approach we call an inverse moth-eye surface, which can be significantly easier to fabricate and more mechanically robust while still providing good broadband AR behavior. This new structure, illustrated in figure 2a, is formed by drilling multi-level sub-wavelength holes of various diameters into a non-absorptive substrate.

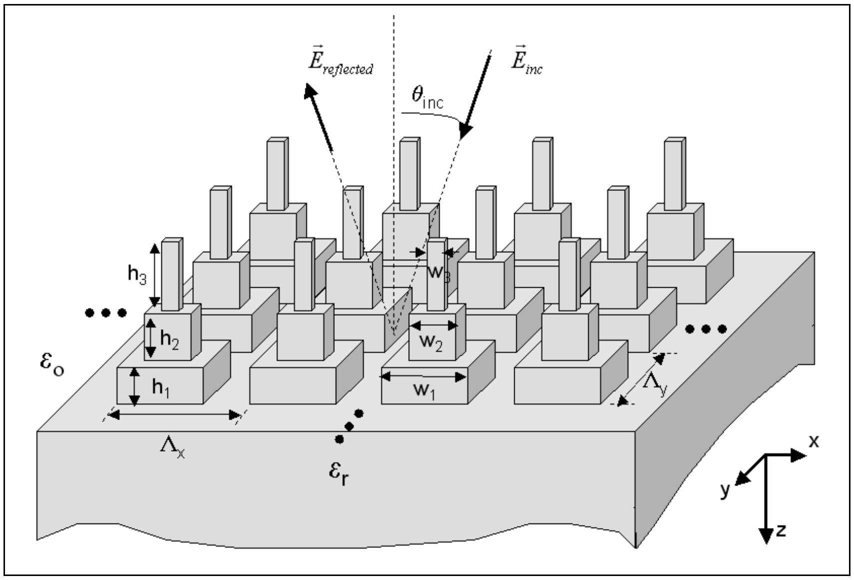

Figure 1. Illustration of a conventional moth-eye AR surface.

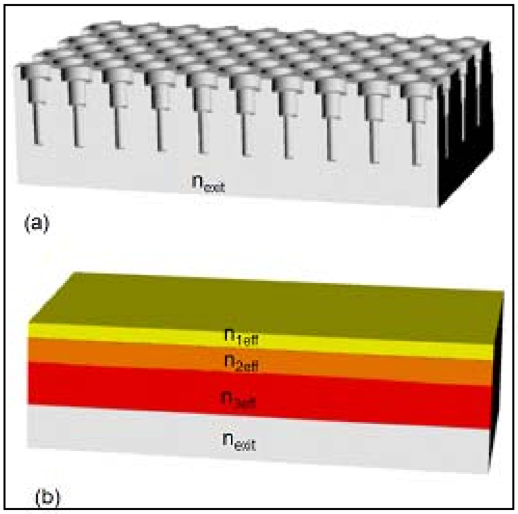

Figure 2. The multi-level, inverse moth-eye, sub-wavelength grating shown in (a) is approximated by an antireflective interference filter shown in (b). The equal ripple antireflective coating (ERAR) algorithm was used to determine the effective properties and thickness of each layer.

An initial design of an inverse moth-eye structure can be performed directly by mapping the "effective" properties of the sub-wavelength structure to the dielectric properties of a multi-layered dielectric stack. This makes intuitive sense given that the discretely varying hole diameters in the inverse moth-eye surface produce layers of different indices of refraction. The first step was to employ conventional AR coating design algorithms to construct an interference filter (figure 2b). While there are a large number of good algorithms for designing antireflective interference filters, we chose to implement the ERAR algorithm originally described by Collin (*4–7*). In Collin's method each layer of a multilayered dielectric stack is designed to be of quarter wavelength phase thickness at the center frequency, f_o, of the band of interest (i.e., $\phi(f_o)=90°$). The next step was to construct a multi-layered sub-wavelength grating in which each layer had the same thickness and "effective" refractive indices as the multi-layered design found via Collin's method. We then assumed that when single level sub-wavelength gratings are stacked to produce a multi-level structure the effective properties of the stacked levels could be approximated by the effective properties of each single layer. We fully acknowledge that in a multi-level grating the effective properties will depend on the upper and lower boundary conditions of each level in addition to being frequency dependent. However, as illustrated later by examples, this direct design method did provide reasonably good results. Most often the grating designs generated by this direct method provided an excellent starting point for the next step. An optimization algorithm, based on a direct pattern search, integrated with a rigorous electromagnetic model (rigorous coupled wave (RCW) algorithm) was then applied to form the final grating geometry. The objective function we chose to minimize was simply the sum of

squared reflection coefficients, r, at a discrete number of frequencies within the band of interest, f_i, and a discrete number of angles of incidence, θ_j, as given by equation 1. This gave very good results, as will be shown in section 3.

$$F = \min\left[\sum_{j=1}^{M}\sum_{i=1}^{N}\left|r(f_i,\theta_j)\right|^2\right] \tag{1}$$

3. Results

An inverse moth-eye AR surface was designed in Rexolite to reflect a minimum amount of energy within the Ka-band (27–40 GHz) at normal incidence. We assumed that the substrate in which the AR surface would be formed had a dielectric constant of ε_r=2.56 and was infinitely thick (i.e., half-space). We also used only a two-level grating as depicted in figure 3. The grating period, Λ, was fixed at 3.1 mm but the grating heights, h_1 and h_2, and hole diameters, d_1 and d_2, were assumed variable. Figure 3 shows the geometrical design results using the direct and iterative methods. It is interesting to note that the direct method does a reasonable good job predicting the final iterative design. In fact, the iteratively refined design did not change any of the initial design parameters by more than 10%.

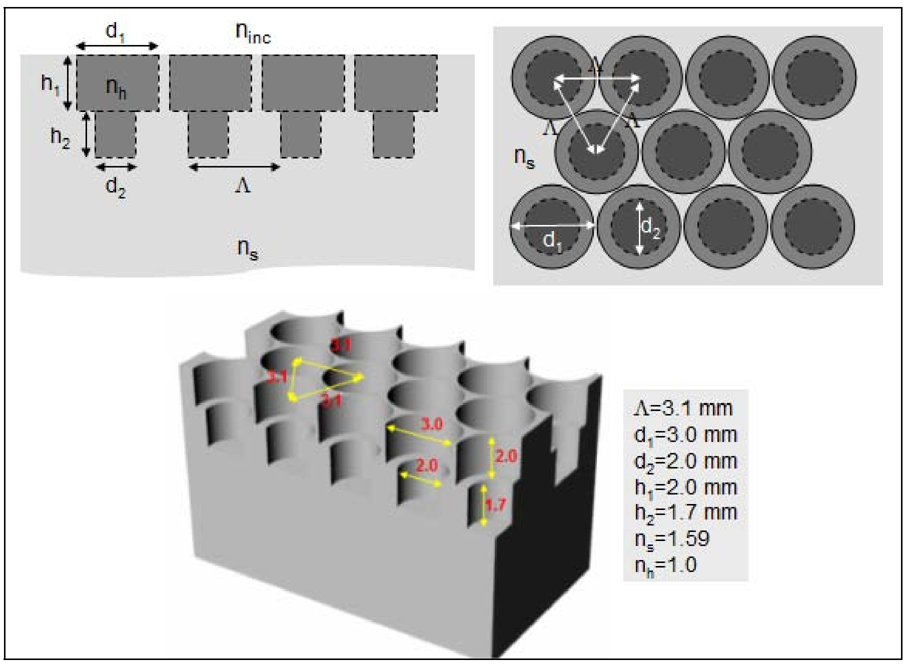

Figure 3. Inverse moth-eye AR surface machined from Rexolite and designed within the Ka-band (27–40 GHz).

Figure 4 shows the results of testing and modeling on this surface. The measurements show a 15–20 dB average reduction in reflectivity across the 30–40 GHz band compared to the surface with no AR treatment. Not only is the magnitude of the improvement impressive, but so is the wide effective bandwidth. This compelling result demonstrates the ability of the technique to significantly reduce surface reflection in MMW imager optical systems.

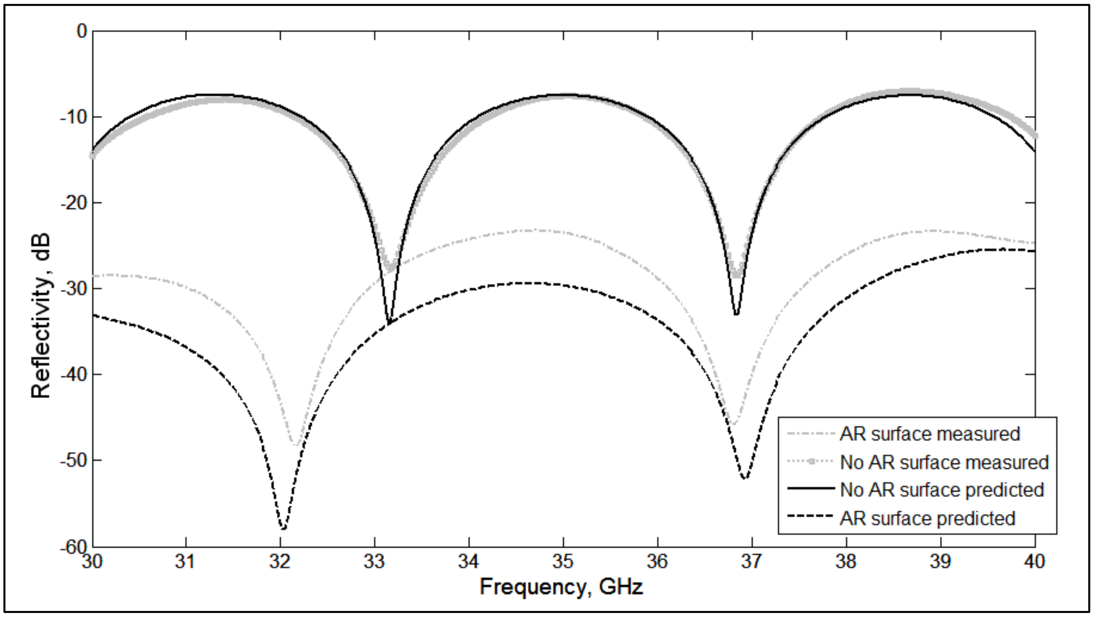

Figure 4. Measured and modeled Rexolite surface normal reflectivity for the Ka-band with and without an AR treatment.

As stated earlier, we also explored how this type of AR grating could be applied to high dielectric materials to reduce surface reflections in MMW imaging systems. An Emerson Cuming product called Eccostock HiK, which has a high dielectric constant and low loss, was identified as a candidate material. This material is a plastic that has a dielectric mixed in during fabrication to produce the desired electrical properties. We used a HiK material with a dielectric constant of 9 and found that it could be machined with the desired AR grating. Transmission was measured at Ku band and the results are shown in figure 5. A dramatic improvement in transmission is seen with the AR surface.

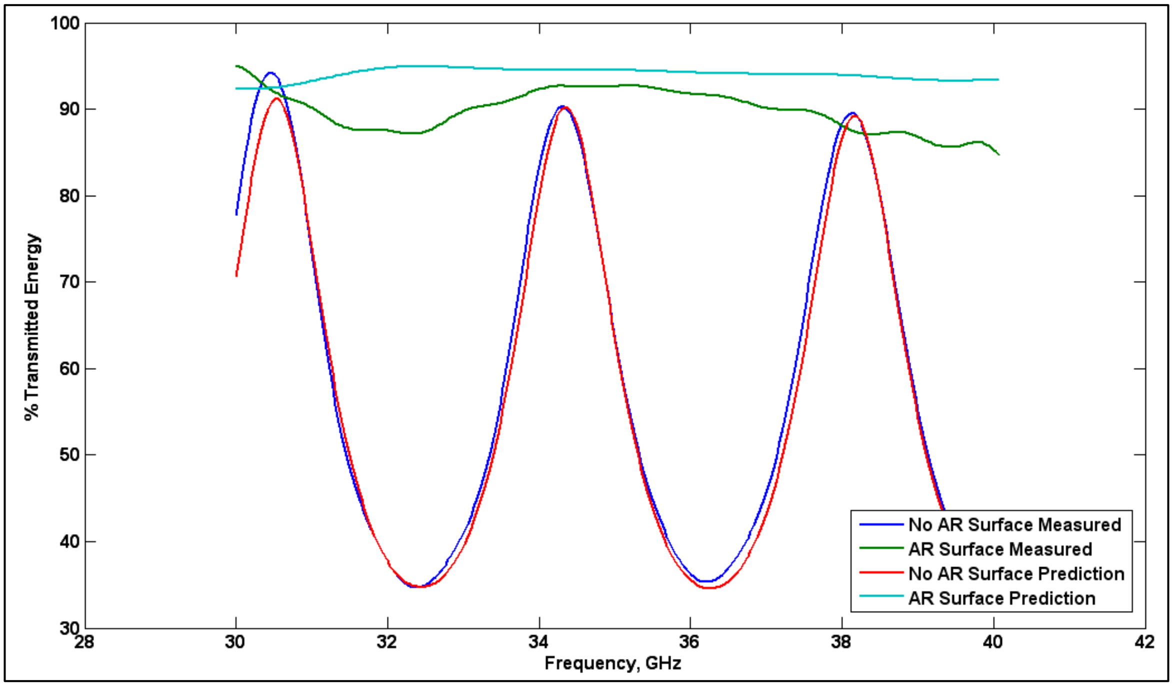

Figure 5. Transmission measured and modeled the Eccostock HiK surface normal reflectivity for the Ka-band with and without an AR treatment.

4. Conclusions

We have modeled, fabricated, and measured AR surfaces for MMW imaging applications based on gratings machined in Rexolite and the HiK material. The grating geometry was designed using a direct approach based on Collin's optical AR method and then optimized with an iterative electromagnetic model. Reflection and transmission were measured for the materials with a 15-dB reduction in surface reflections seen in Rexolite and better than 90% transmission in the HiK material. These results give us reason to believe that properly treated high dielectric materials have the potential to significantly reduce the volume and weight of MMW optical systems without degrading performance.

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6. Transitions

The following has been submitted to the IEEE Antennas and Propagation conference:

"Design of Transparent Dielectric Windows at RF Frequencies Using Moth-Eye Anti-reflective Surfaces," M. S. Mirotznik, B. Good, K. Barry, D. Wikner, J. N. Mait, and P. Ransom.

Acronyms

AR	anti-reflection
ARL	U.S. Army Research Laboratory
DRI	Director's Research Initiative
ERAR	equal ripple antireflective coating
MMW	millimeter-wave
RCW	rigorous coupled wave
RF	radio frequency

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